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Strange meson enhancement in PbPb collisions

NA44 Collaboration

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Abstract

The NA44 Collaboration has measured yields and differential distributions of K^+ , K^- , π^+ , π^- in transverse kinetic energy and rapidity, around the center-of-mass rapidity in 158 A GeV/c Pb + Pb collisions at the CERN SPS. A considerable enhancement of K^+ production per π is observed, as compared to $p + p$ collisions at this energy. To illustrate

the importance of secondary hadron rescattering as an enhancement mechanism, we compare strangeness production at the SPS and AGS with predictions of the transport model RQMD. © 1999 Published by Elsevier Science B.V. All rights reserved.

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1. Introduction

Ultrarelativistic heavy ion collisions create a highly excited complex system, whose dynamics are governed by excitation of nucleonic, mesonic, resonance [1] and, to some unknown extent, quark and gluon degrees of freedom. It has been predicted that the extreme conditions of temperature and density in such collisions may suffice to create a state, known as quark–gluon plasma (QGP), where the quarks are no longer confined in hadrons [2]. This has stimulated experimental searches for evidence of the deconfinement phase transition. Interactions between liberated gluons in the deconfined phase are predicted [3] to enhance the rate of strangeness production compared to the non-QGP scenarios.

Being the lightest strange hadrons, kaons are expected to dominate the strange sector by virtue of canonical thermodynamics [4]. The observed kaon multiplicity yields information about the mechanism of strangeness production, hadronization and subsequent evolution in the hadron gas, before the gas

becomes sufficiently dilute that the interactions cease. Inelastic hadronic rescattering can enrich the strangeness content of the system [5]. We report the yields and distributions of charged kaons and pions measured in ultrarelativistic PbPb collisions by the NA44 Experiment, and discuss implications of these data on the physics of the above-mentioned hadronic processes.

2. Experiment and data analysis

The NA44 Collaboration has measured PbPb collisions at 158 A GeV/c using a focusing spectrometer at the CERN SPS. A magnet system of two dipoles and three focusing quadrupoles, together with a tracking complex (a pad chamber, three highly segmented scintillation hodoscopes H2, H3, H4 and two strip chambers) provides momentum resolution of 0.2% or better for all spectrometer settings. The spectrometer accepts charged particles of a single charge at a time, has two angular positions (44 and 131 mrad) and is operated at two different field strengths. In the weak field mode, it accepts charged tracks in the momentum range of $3.3 < p < 5.1$ GeV/c, and of $6.3 < p < 9.7$ GeV/c in the strong field mode. These two field modes are often called “the 4 GeV/c” and “the 8 GeV/c” settings, respectively. More details about the spectrometer are given in [6].

Low (predominantly single track) multiplicity in the spectrometer acceptance allows use of two Cherenkov counters (C1, C2) for threshold discrimination of particles of different mass. Collection of K/p and π samples uses different trigger requirements: in the K/p mode, the absence of pions and electrons in the acceptance is enforced by a Cherenkov veto (on C1, or both C1 and C2, depending on the momentum setting), whilst for pions, no special trigger enrichment is needed.

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Separation of kaons from protons in all settings is performed off-line using the time-of-flight difference between K and p . The time-of-flight is measured using the beam counter [7] (with 35 ps resolution) as start and H3 (with 100 ps resolution) as stop. In the weak magnetic field mode, the pions used in this analysis are identified by time-of-flight, while events with electrons in the acceptance are rejected off-line using C2. In the strong field mode, kaons and protons are separated from pions by Cherenkov and time-of-flight. High ($\geq 98\%$) purity of the K and π samples is achieved in all spectrometer settings.

Inefficiencies due to the Cherenkov vetoes are evaluated by measuring the rejection by the Cherenkovs in untriggered runs. Such unwanted vetoes occur when a kaon or proton is accompanied by a pion, electron or muon in the Cherenkov counters. To evaluate the inefficiency in the weak magnetic field runs, the vetoed kaons are identified by time-of-flight and the Uranium calorimeter [8] data is used for π/e separation. In the strong magnetic field runs, the momentum of the particles is too high for reliable separation by time-of-flight, and subtraction of pions, utilizing knowledge of the pion line shape in m^2 , is used to count vetoed kaons.

NA44 has two detectors to characterize event multiplicity: T_0 (a scintillator trigger counter covering $1.4 \leq \eta \leq 3.7$ for an η -dependent fraction of azimuthal angle, $0.22 \leq \Delta\phi/2\pi \leq 0.84$ respectively), and a Si pad array measuring dE/dx in 512 pads covering $1.5 \leq \eta \leq 3.3$ and 2π azimuthally. The multiplicity of a given particle in the spectrometer is an average over many events of a certain centrality class, set by a cut on T_0 . The T_0 centrality scale was calibrated by requiring agreement between the normalized yield of charged particles in the spectrometer and the multiplicity in the silicon. Correction for the acceptance difference between the spectrometer and the Si array is performed using the RQMD model [9], which is consistent with measured [10] charged hadron distributions. Kaon and pion samples of identical centrality are selected via the T_0 signal amplitude.

Differential distributions of particles in rapidity, y , and transverse kinetic energy, $m_T - m$, carry information about the dynamics of the collision. In determining dN/dy for kaons and pions we use spectrometer settings, or portions thereof, with Δy

$= 0.2 - 0.6$. The slope parameter(s) do not depend on y within this small range. Then

$$\begin{aligned} \left\langle E \frac{d^3N}{dp^3} \right\rangle_{\Delta y, 2\pi} &= \frac{1}{2\pi} \left\langle \frac{dN}{m_T dm_T} \right\rangle_{\Delta y} \\ &= \frac{dn}{m_T dm_T} \int_{\Delta y} \frac{d\tilde{N}}{dy} dy \\ &= \frac{2\pi \Delta y \int_{\Delta y} A \frac{d\tilde{N}}{dy} dy}{2\pi \Delta y \int_{\Delta y} A \frac{d\tilde{N}}{dy} dy}, \end{aligned} \quad (1)$$

where $A = A(y, m_T)$ is the acceptance function from Monte Carlo simulation of the spectrometer, including effects of magnetic optics, detector response, momentum resolution, tracking efficiency and decays. Typically it is dominated by the trivial factor $\Delta\phi/2\pi$ representing the azimuthal acceptance of the spectrometer. Within the spectrometer acceptance at $p_T = 0.4$ GeV/ c for a midrapidity pion, the remaining factors would amount to about 0.5. dn/dm_T is the number density of reconstructed tracks in m_T . $d\tilde{N}/dy$ is the shape of the rapidity distribution, taken to be Gaussian around midrapidity. Integration of the m_T distribution with extrapolation to $m < m_T < \infty$, using the fitted slopes, results in dN/dy .

Table 1 shows the sources of systematic uncertainty on dN/dy . The error in the extrapolation due to uncertainty in the slope parameter(s) is small because over 95% of particles around mid-rapidity have p_T in the range covered by one of the two angle settings. Consequently, the systematic error in dN/dy is dominated not by the extrapolation, but by uncertainties in determination of centrality and particle ID efficiency. The systematic uncertainty due to centrality was determined from the setting-by-setting variation of acceptance corrected yields of charged

Table 1

Summary of fractional systematic errors to the normalized yields. Positive kaons in the weak field high angle spectrometer setting are chosen as “representative”. Maximum and minimum uncertainties indicate the range; the overall systematic uncertainty was evaluated for each setting separately.

Case	Centrality	PID	p_T extrapolation	Total
representative	0.081	0.042	0.0067	0.098
maximum in any setting	0.081	0.25	0.063	0.26
minimum in any setting	0.058	0.014	0.0042	0.058

Table 2
Inverse slope parameters T .

PID	y interval	T (MeV)	$\sigma(T)$ stat., syst. (MeV)
K^+	2.3–2.6	230	$\pm 8 \pm 14$
K^+	2.4–2.9	254	$\pm 4 \pm 7$
K^-	2.3–2.6	259	$\pm 8 \pm 12$
K^-	2.4–2.9	245	$\pm 7 \pm 6$

tracks, without requiring particle ID. The uncertainty due to PID efficiency corrections arises from statistical uncertainties in the particle counts in untriggered runs used to determine the veto correction.

3. Results and discussion

Tables 2 and 3 give the m_T slope parameters and values of dN/dy for kaons and pions. The measured distributions for charged kaons of both signs in transverse kinetic energy and rapidity, are shown on Fig. 1¹² and Fig. 2, respectively.

The $1/m_T$ scaled spectra appear exponential in accordance with the behaviour typical for thermalized ensembles of interacting particles, or for particles in whose production the phase-space constraints played the dominant role [11]. The spectra were fit with an exponential in $(m_T - m)$, and the resulting slopes are shown in the inserts in Fig. 1. The inverse slopes of the K^+ and K^- spectra are the same, within errors. Our event selection is sufficiently central that the slopes show no dependence on multiplicity.

In Fig. 2, it is clear that many fewer kaons are produced than pions, as was observed in $p + p$ collisions. There are approximately twice as many positive as negative kaons produced. This is typical for baryon rich systems, and was also observed in $p + p$ collisions. Preliminary NA49 measurements of K^+ and K^- dN/dy [12] are consistent with those reported here.

Both Fig. 1 and 2 compare the data with predictions of the transport theoretical approach RQMD

Table 3

Particle distributions in rapidity. Every spectrometer setting provides an independent measurement. Settings overlapping in y are listed separately. Statistical and systematic errorbars are added in quadrature to form $\sigma(dN/dy)$ listed.

PID	y interval	dN/dy	$\sigma(dN/dy)$
4% centr. K^+	2.7–2.9	37.1	± 5.4
	2.3–2.6	27.2	± 2.5
	3.1–3.4	29.7	± 5.6
	2.6–2.8	33.6	± 3.1
4% centr. K^-	2.7–2.9	21.5	± 7.5
	2.3–2.5	18.7	± 1.9
	3.1–3.4	15.4	± 4.1
	2.6–2.8	14.8	± 1.4
4% centr. π^+	3.3–3.7	160	± 15
	2.6–2.9	153	± 10
	3.5–4.0	145	± 10
	2.6–2.9	164	± 13
4% centr. π^-	3.3–3.7	176	± 14
	2.6–2.9	193	± 12
	3.5–4.0	173	± 12
	2.6–2.9	173	± 15

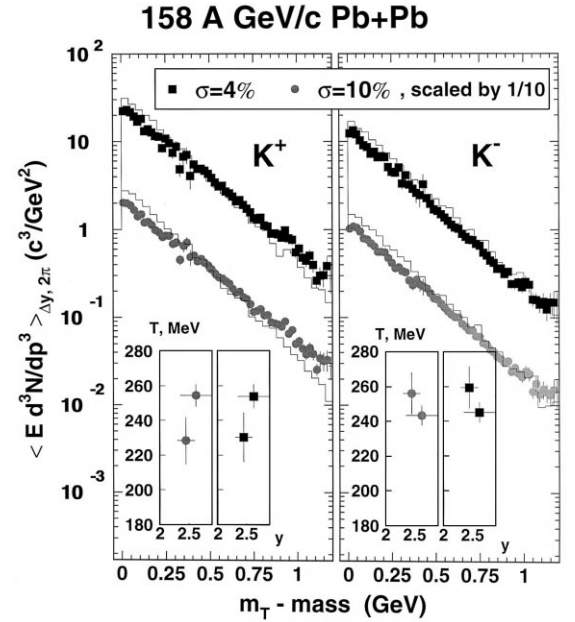


Fig. 1. Measured transverse kinetic energy distributions of positive and negative kaons for the 4% and 10% most central of Pb + Pb collisions. Two spectrometer angle settings meet at $m_T - m = 0.35$ GeV. The fits follow the form $1/m_T dN/dm_T \propto \exp(-m_T/T)$, where $m_T = (m^2 + p_T^2)^{1/2}$. y ranges of the fits are given in Table 2 and are indicated by the horizontal errorbars in the inserts. RQMD predictions for $|y - y_{CM}| < 0.6$ (i.e., within NA44 acceptance) are shown as histograms.

¹² Experimental data on this figure can be retrieved electronically from The National Nuclear Data Center.

[9]. While RQMD tends to overpredict both the K^+ and K^- yields, for K^- the discrepancy appears to be larger. Running RQMD in the mode which does not allow the hadrons to rescatter (shown by the dashed line on the figure) decreases the number of kaons produced. This result illustrates the importance of the secondary scattering to the total kaon yields. Measurements of proton production at midrapidity [13] and of the $p - \bar{p}$ rapidity distribution [14] indicate that RQMD somewhat overpredicts the degree of baryon stopping. Because πN inelastic collisions can produce kaons, an increase in stopping translates naturally into kaon enhancement at midrapidity. The data show that the hadron chemistry via secondary scattering, as implemented in RQMD, successfully reproduces the general trends in the hadron distribution. However, the hadron chemistry in the model is not quantitatively correct.

Exothermic strangeness exchange reactions of the kind $K + N \rightarrow Y + \pi$ and $\bar{K} + \bar{N} \rightarrow \bar{Y} + \pi$ are

158 A GeV/c Pb+Pb 4% central

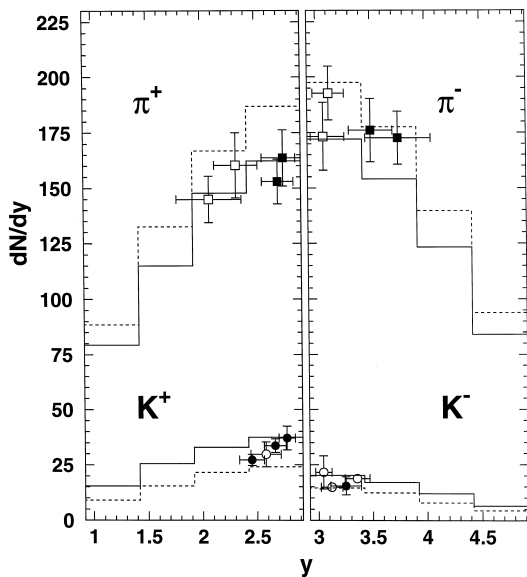


Fig. 2. Comparison of measured charged kaon and pion yields with RQMD predictions. The vertical error bars indicate statistical and systematic errors, added in quadrature; the horizontal ones – y boundaries of the acceptance used for p_T integration in each spectrometer setting. Open symbols represent spectrometer settings whose y position is shown mirror-reflected around midrapidity (2.92); their solid analogs – the actual settings. RQMD: solid line – standard mode, dashed line – no rescattering.

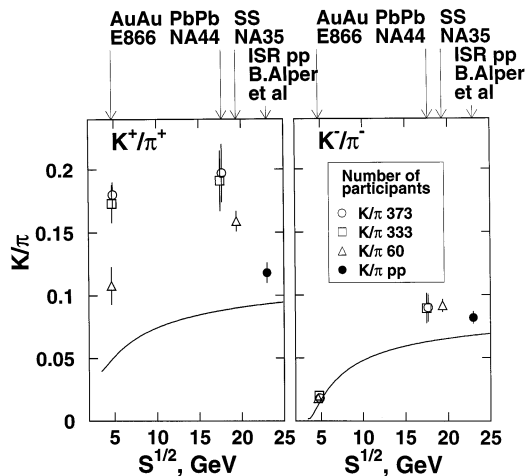


Fig. 3. K/π ratios in symmetric systems at midrapidity $|y - y_{CM}| \leq |y_{proj} - y_{targ}|/8$. The solid line shows full solid angle K/π in $p + p$ collisions from the interpolation [19]. The data points from other experiments result from an interpolation in y to the midrapidity interval. The E866 data points [17] are also interpolated in the number of participants, for comparison with the SPS data.

favoured by the cooling of the system, and redistribute strangeness from the mesonic to the baryonic sector. If larger systems reach lower temperature before freezing out [15], such reactions may be important in Pb + Pb collisions. These strangeness processes are in RQMD. The model seems to underpredict (preliminary) Λ yields [12] and overpredict K^- . This may indicate that the details of the description should be reexamined.

The K/π abundance ratio allows estimation of the degree of strangeness enhancement and comparison of various colliding systems. Fig. 3 summarizes the existing midrapidity data in symmetric systems: ISR $p + p$ [16]; AGS AuAu [17]; SPS SS [18]; and SPS PbPb.¹³ Strangeness enhancement compared to the interpolated [19] pp collision data, shown as the line, is seen. The solid point, corresponding to ISR data at midrapidity, indicates the extent of the en-

¹³ In this figure, as well as in Fig. 4, the hadron abundances we present are integrals over a fixed fraction of rapidity around midrapidity y_{CM} : $|y - y_{CM}| \leq |y_{proj} - y_{targ}|/8$. This enables the comparison between various energies and experiments, but involves an interpolation in y for experiments with larger coverage.

hancement due to the midrapidity cut on the particles. The figure shows that K^+/π^+ is enhanced in high multiplicity heavy ion collisions, but K^-/π^- is consistent with $p + p$ values. Higher multiplicity, or more central collisions, yields larger enhancement, independent of \sqrt{s} .

Secondary hadronic interactions of the type $\pi + N \rightarrow Y + \bar{K}$ are important for the strangeness production [1,20], and their rate is proportional to the product of the participant's effective concentrations. Fig. 4 shows the dependence of the K^+/π^+ ratio on the product of rapidity densities of the two ingredients of the associated strangeness production, N (represented by p) and π^+ in the AGS [21] and SPS [22] data, and RQMD calculations. This “ $p \times \pi$ ” product serves as an observable measure of the strangeness-enhancing rescattering. The rate of change in the K^+/π^+ ratio with this rescattering observable is initially very high. However, K^+/π^+ nearly saturates after this initial rise. The figure shows why the enhancement is large as soon as the multiplicity becomes appreciable. The values of “ $p \times \pi$ ” reached at the SPS and AGS are comparable, explaining the similarity of the kaon enhancement despite the different energies. RQMD reproduces the trend of the data very well, and the dotted lines (illustrating no rescattering) along with the shape of the rise with “ $p \times \pi$ ” underscore the role of

hadronic rescattering in kaon yields. The quantitative agreement of RQMD with the data is not as good, but the final results are undoubtedly quite sensitive to the magnitude of the cross sections used in the model.

4. Conclusions

Production of charged K and π mesons in central Pb + Pb collisions at 158 GeV/nucleon has been measured. Within the centrality range studied, no strong multiplicity dependence of the kaon m_T slopes or K/π ratios has been observed. We see no significant slope difference between K^+ and K^- . K^+/π^+ is enhanced by a factor of about two over $p + p$ collisions, whereas K^-/π^- is little enhanced. Our measurement of K^+/K^- in this saturated region may be used for chemical calculations of the hadron gas.

Comparison with the RQMD model shows that the model qualitatively reproduces the hadron chemistry, through the rescattering of the produced particles. Quantitative comparisons, however, show that the model overpredicts the K^- , while the magnitude of K^+ enhancement is within the range explainable by the RQMD mechanisms. Deconfinement scenarios of the K^+/π^+ enhancement can not, however, be ruled out or proven by these data alone.

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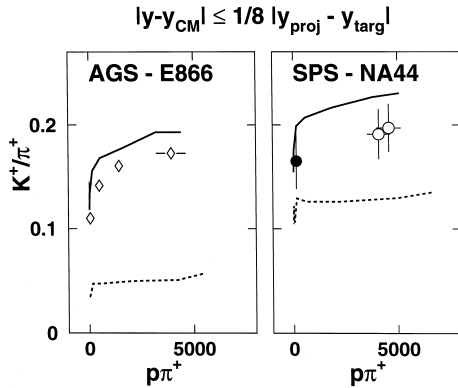


Fig. 4. Comparison of measurements with RQMD predictions: K^+/π^+ ratio in the specified rapidity interval around mid-rapidity, as a function of the product of pion and proton dN/dy , obtained in the same rapidity interval, in symmetric collisions. \diamond – E866 AuAu, \bullet – NA44 SS, \circ – NA44 PbPb. RQMD: solid line – standard mode, dashed line – no rescattering.

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